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THE CONSTRUCTION OF A TIMBRE TEST

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THE CONSTRUCTION OF A TIMBRE TEST*

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Introduction. The need for a test of the "sense of timbre," to supplement the Seashore measures of musical talent, has long been felt. The development of such a test, necessarily delayed for many years because suitable apparatus was not available, finally became possible after the optical generator had been built.[1] This paper is designed to describe the construction of the test (which is still in tentative form) and to summarize data which have been secured concerning it. The presentation of norms and final reliability coefficients, together with material on validity, must await the revision of the test and the recording of it on standard phonograph records.

Preparation of the stimulus series. After preliminary measurements of capacity to discriminate timbre had been made, a disc was constructed, for use on the generator, with which 6 different complex tones could be produced. The tones had a fundamental frequency of 180 cycles. They were alike in both pitch and loudness[2] but differed in timbre. The timbre variations were due, almost entirely, to changes in the relative intensity of two of the partials used.

With the 6 tones, 15 different pairs of tones could be studied. These various pairs were evaluated by means of the method of

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[1] A description of the generator will be found in the appendix.

[2] The tones were equated in physical intensity and were, presumably, of equal loudness. While it is true that loudness is not dependent solely upon intensity, the other factors which contribute to differences in the loudness of complex sounds were probably not operative. The major variations in relative intensity of partials occurred in adjacent partials (the 3rd and 4th) and at frequencies (540 and 720 cycles) between which loudness varies only slightly with frequency. Furthermore, critical observers could not detect differences in loudness.

paired comparisons. That is, measurement was made to determine the relative ease with which a group of unselected observers could detect timbre differences between the members of the pairs. Five of the pairs which seemed to cover a sufficiently great range of difficulty were chosen. The 2 tones of each of these 5 pairs were then arranged into a series of 20 stimulus pairs, of which 10 were the same and 10 different in structure. Half of the "same" pairs in a single series were composed of one of the tones; the other half of the other tone. The "different" pairs were arranged in random order and scattered among the "same" pairs.

There were 5 series in all. These series were recorded on phonograph records. The test was thus constituted of 5 series of 20 stimulus pairs each; 100 stimulus pairs in all. Fifty of the stimulus pairs were the same in harmonic structure, while the other 50 were different in this respect. Each stimulus tone, as recorded, had a duration of 1.5 sec. There was an interval of 0.5 sec. between members of a pair, and of 3 sec. between pairs. Each series of 20 pairs was recorded separately, with a pause of 20 sec. after the first 10 pairs. A rest period of about 40 sec. was given between series. Slightly less than 15 minutes were required for the administration of the whole test.

Harmonic structure of the stimulus tones. Oscillograms of the 2 tones used in each of the 5 series were taken from the phonograph records. The results of the analysis of these oscillograms are given in Fig. 1, in the form of acoustic spectra. The plotted values no doubt approximate the true stimulus values.[3]

The over-all difference between the relative intensities of corresponding partials of the 2 tones of each series was determined by computing the sum of the differences among the percentage values for the partials, as plotted in Fig. 1. The computed dif-

[3] The spectra in Fig. 1 are not strictly correct, of course. Aside from the small error due to the analyzing process proper, an error of indeterminate magnitude must be attributed to aperiodicities caused by surface noise. Another point which deserves mention is that the oscillograms were taken from a large studio, with the microphone about 7 feet from the loud speaker of the phonograph. Because of the reverberant character of the studio, any other distance would undoubtedly have yielded somewhat different results.

ferences for the 5 series are given in Table I. For example, in Series 1, which was the least difficult in the test, the distribution of energy in the partials of one of the tones differed 58% from the distribution in the other tone. In Series 5, which was the most difficult, the 2 tones differed in energy distribution by 18%.[4]

TABLE I

GROSS DIFFERENCES IN DISTRIBUTION OF ENERGY IN THE PARTIALS OF THE 2 TONES OF EACH OF THE 5 STIMULUS SERIES

Series	Difference in %
1	58
2	49
3	42
4	29
5	18

Administration of the test. The test was first administered to 317 university students who were enrolled in classes in elementary psychology, and subsequently to 62 members of the university orchestra. The following instructions were used:

> "You will be presented with a number of pairs of tones. The 2 tones of some of the pairs will be heard as the same in timbre, while the 2 tones of the other pairs will be heard as different in timbre. If, in your opinion, the 2 tones of a pair are the same in timbre, record S; if they are different, record D. Be sure to pass judgment on each pair.
>
> "You are asked not to move your head during the presentation of a pair of tones."

The observers were given a short practice period during which timbre differences were demonstrated.

[4] It would be possible to express the differences among the relative intensities of the various partials of a pair of tones in intensity level units (decibels), but such a procedure would probably only complicate the treatment of test results. Careful psychophysical investigations of timbre would call for a highly detailed and exact description of stimulus tones, but all that is needed for present purposes is a gross measure of structural differences.

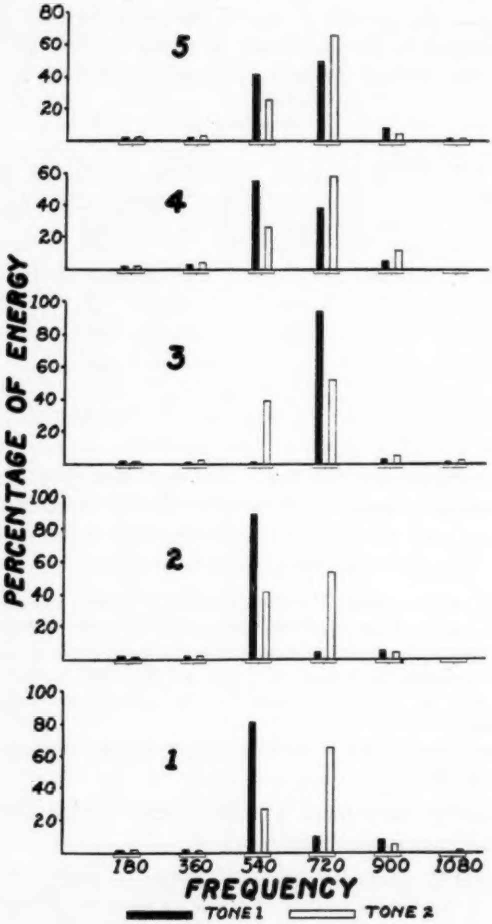

Fig. 1

Acoustic spectra of the 2 tones used in each of the 5 series of the timbre test.

Preliminary treatment of test results: (a) Scoring. Each person who took the test was given 8 different raw scores. The first score was based upon the number of correct responses obtained in the whole test; the second upon the number of correct responses to the odd pairs of the whole; and the third upon the number of correct responses to the even pairs. The remaining 5 scores were based upon the number of correct responses obtained in the 5 series, each series considered as a unit. The 8 raw scores were then converted into percentage scores; and all computations were made from the latter. Scores secured by the psychology students were kept separate from those secured by the orchestra members.

(b) Frequency distributions of scores on the whole test. Frequency distributions of scores secured on the whole test by the psychology students and by the orchestra members are plotted in Fig. 2. The range for the psychology students was 44 (from 49 to 93); for the orchestra members, 36 (from 62 to 98). Other facts about the distributions are given in Table II.

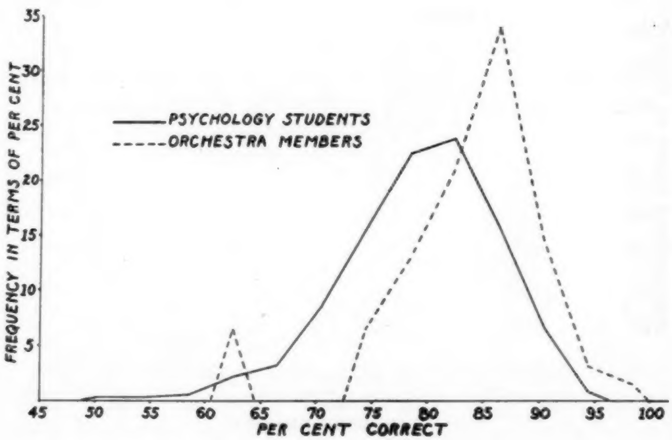

Fig. 2

Frequency distributions of scores obtained on the timbre test by 317 psychology students and 62 members of the university orchestra.

TABLE II
MEANS, STANDARD DEVIATIONS, AND PROBABLE ERRORS OF THE MEANS OF THE DISTRIBUTIONS SHOWN IN FIG. 2

Distribution	N	M	SD	PE_M
Psychology students	317	79.3	7.0	.27
Orchestra members	62	83.5	7.3	.63

On the whole, the test was less difficult for the orchestra members than it was for the psychology students. The difference between the 2 means is statistically significant (CR = 6.2).

(c) Reliability coefficients. As has been indicated, each person was given a score based upon the number of correct responses to the odd pairs of the test and another score based upon responses to the even pairs. Correlations were run between these 2 scores, for both psychology students and members of the orchestra; and the coefficients were used in the Spearman-Brown prophecy formula to secure reliability coefficients for the test. The results were .68

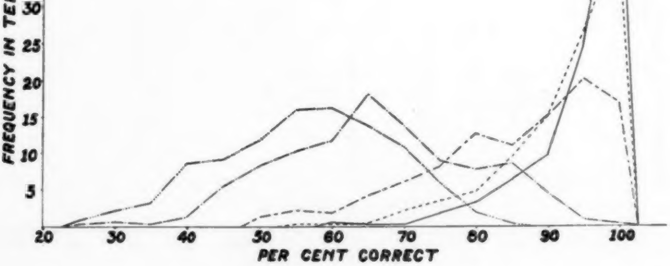

Fig. 3

Frequency distributions of scores obtained by 317 psychology students on each of the 5 series of the timbre test.

and .71 for psychology students and orchestra members, respectively. These coefficients, although not unusually high, compare favorably with reliability coefficients that have been obtained for the Seashore measures.

Internal checks on the test: (a) Frequency distributions of scores on the individual series. As a first means of checking the test, frequency distributions were made of the scores obtained by the psychology students on each of the 5 series. These distributions are graphed in Fig. 3. Statistical values for the distributions are given in Table III. It will be seen that the polygons for Series 1 and 2 are quite similar and that the difference between the mean for Series 1 and the mean for Series 2 is quite small. Also, the difference between the means for Series 3 and 4 is quite large. It is apparent that the test would undoubtedly be improved, at least for use with adults, if either Series 1 or Series 2 were eliminated and a new series were added whose mean would fall about midway between the means for Series 3 and 4. Such a series would probably have to be composed of 2 tones, similar to those already employed, whose partials differed in relative intensity by about 35%. (See Table I.)

TABLE III

MEANS, STANDARD DEVIATIONS, AND PROBABLE ERRORS OF THE MEANS OF THE DISTRIBUTIONS SHOWN IN FIG. 3

Distribution	N	M	SD	PE_M
Series 1	317	95.2	7.0	.27
2	317	93.3	8.0	.30
3	317	85.4	12.5	.48
4	317	66.3	13.0	.50
5	317	56.4	12.0	.46

(b) Correlations between scores on the individual series and scores on the whole test. A second internal check on the test was made by running correlations between the scores obtained on each series and on the whole test, by the psychology students. The coefficients, which are given in Table IV, indicate in a general way to what extent each series operated in the determination of total

scores. As would be expected, the coefficients for Series 1 and 5 (the least difficult and the most difficult, respectively) are the lowest of the five. Series 3, with a coefficient of .78, must be designated as the most influential one in the test. Inasmuch, however, as all of the coefficients are relatively high, no one of the series may be regarded as wholly ineffectual for use with adults.

TABLE IV

COEFFICIENTS OF CORRELATION BETWEEN SCORES ON EACH SERIES AND SCORES ON THE WHOLE TEST. (PSYCHOLOGY STUDENTS)

Series	r
1	.62
2	.66
3	.78
4	.68
5	.52

(c) Correlations between scores on the individual series. A further check on the test was made by running correlations between the scores obtained by the psychology students on the individual series. That is, scores on every series were correlated with scores on every other series. The coefficients are given in Table V. A low coefficient indicates that the 2 series involved were markedly different in differentiating powers; a relatively high coefficient just the opposite. None of the coefficients is sufficiently high to justify the conclusion that any series was of no importance whatever.

TABLE V

COEFFICIENTS OF CORRELATION BETWEEN SCORES OBTAINED BY THE PSYCHOLOGY STUDENTS ON THE INDIVIDUAL SERIES

Series	r	Series	r
1 & 2	.45	2 & 4	.24
1 & 3	.43	2 & 5	.19
1 & 4	.31	3 & 4	.40
1 & 5	.15	3 & 5	.16
2 & 3	.51	4 & 5	.11

(d) Differentiating powers of the 5 series at different levels of ability. As a means of determining how the various series functioned to differentiate among individuals at different levels of ability, 300 of the psychology students were first selected at random and divided into 5 groups on the basis of their scores on the whole test. Then, the mean of the scores obtained by the members of each group on each series was computed. The values are plotted in the left-hand graph of Fig. 4. The students in Group 1 were those whose scores on the whole test placed them in the lowest 20% of the whole distribution; students in Group 2, those in the next higher 20%, and so on.[5]

The curves in the left-hand graph of Fig. 4 give a clear picture of the functioning of the various series at the 5 different levels of ability. The data from which they were plotted warrant the following generalizations: Group 1 was differentiated from Group 2 by Series 1, 2, 3, and 4 (Series 3 predominating); Group 2 from Group 3, by Series 3, 4, and 5; Group 3 from Group 4, by Series 3, 4, and 5; Group 4 from Group 5, by Series 3, 4, and 5 (Series 4 predominating). It seems likely that Series 1 and 2 would become increasingly important the lower the tested individuals were in the scale of ability, and that Series 5 would be more influential if the test were administered to persons of greater ability. Evidence in partial support of this assumption is presented in the right-hand graph of Fig. 4. The curves here were plotted from the responses made by 5 different groups of orchestra members.[6] The increased importance of Series 5 is obvious. Obvious, also, is the decreased importance of Series 3.

Both sets of curves in Fig. 4 reveal that the gap between Series 3 and 4 is unreasonably large. Slight doubt remains that the test as a whole would be improved if a new series were added whose curve would fall about midway between those for Series 3 and 4.

The "sense of timbre" as related to other auditory capacities. Seashore has said: "The sense of timbre involves a keen sense of

[5] Mean scores for the 5 groups were: Group 1, 68.7; Group 2, 76.1; Group 3, 79.9; Group 4, 83.1; Group 5, 88.0.

[6] Mean scores for these 5 groups were: Group 1, 74.3; Group 2, 81.8; Group 3, 85.0; Group 4, 87.3; Group 5, 91.8.

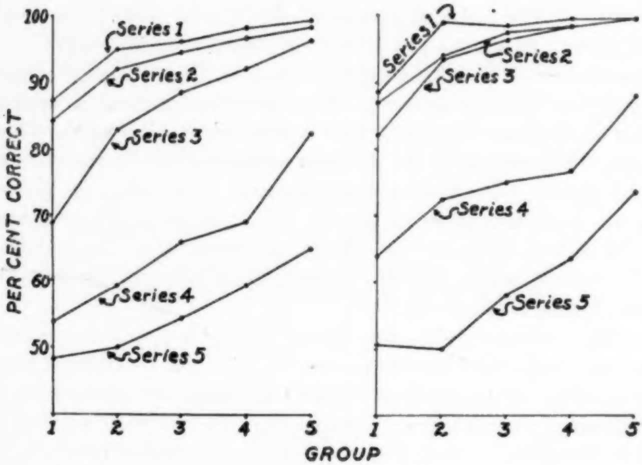

Fig. 4

Curves showing the mean percentage of correct responses made on each of the 5 series in the timbre test by each of 5 sub-groups of psychology students (left-hand graph) and by each of 5 sub groups of orchestra members (right-hand graph).

pitch because, whether consciously or unconsciously, the hearing of timbre is the hearing of a series of overtones present in a clang. . . . The sense of timbre also posits a certain degree of the sense of intensity. For most practical purposes we shall have a correct index to the sense of timbre in terms of the sense of pitch and the sense of intensity . . . together with auditory imagery. . . ."[7]

This viewpoint, insofar as it relates to pitch and intensity (loudness), is not supported by certain results of this study. The orchestra members who took the timbre test also took the Seashore tests of pitch and intensity. The correlation between scores on the timbre test and scores on the pitch test was only .08; between scores on the timbre test and scores on the intensity test, only .18. The "sense of timbre" may, of course, be related to what Seashore calls

[7] Seashore, C. E. The psychology of musical talent. Boston: Silver, Burdett & Company, 1919. pp. 136-137.

auditory imagery, but the present information tends to indicate that ability to discriminate timbre does not vary in any significant manner with ability to discriminate either pitch or loudness.[8]

On thresholds for timbre discrimination. If there is justification for assuming that the difference between the timbres of the 2 tones of a stimulus series may be represented at least in a general way, on the physical side, by the percentage of difference in the distribution of energy in the partials of the 2 tones, then the data secured by means of the timbre test can be used to secure preliminary information on timbre thresholds. But before the data are dealt with, one point should be emphasized. Psychophysical experiments, designed to measure thresholds, are usually conducted under rigidly controlled conditions, and the number of trials given is quite large. In the present instance, proper controls were lacking, and only a few trials were given at each level of difficulty. In short, the data to be summarized were not secured under conditions prescribed by acceptable psychophysical techniques. Consequently, the computed values will be indicative only of general trends.

Threshold values were computed by linear interpolation[9] for the psychology students as a whole and for the orchestra members as a whole, and also for the 5 sub-groups of psychology students and the 5 sub-groups of orchestra members which were used in a part of the study already discussed.

In the left-hand graph of Fig. 5, the mean scores secured by the psychology students and by the orchestra members on each series are plotted against structural differences. The abscissa values are those given in Table I. The middle graph of Fig. 5 is a similar

[8] This conclusion is probably justifiable even though the orchestra members constituted a highly selected group.

[9] The following formula was used:

$$\frac{T - X_1}{X_2 - T} = \frac{75 - P_1}{P_2 - 75}$$

where T is the threshold (for 75% correct response); X_1 and X_2 are the values of the stimulus which subtend the threshold; and P_1 and P_2 are the percentages of correct responses secured with X_1 and X_2, respectively.

plot for the 5 sub-groups of psychology students; the right-hand graph, a plot for the 5 sub-groups of orchestra members. In any one of the three graphs, a given curve shows how the percentage of correct responses increased as the amount of structural difference increased.

Table VI gives threshold values, together with data used in the linear interpolation formula to compute them. No extended discussion of the results will be given. However, it is interesting to note that the threshold values cover a rather wide range. For example, the thresholds for the least able group of psychology students and the least able group of orchestra members are almost twice those for the most able groups. Also, the threshold for the orchestra members (taken as a whole) is about midway between the thresholds for Groups 4 and 5 of the psychology students. The difference in the general capacity of the 2 large samples has already been seen in terms of mean scores secured on the entire test, but the difference is here even more strikingly demonstrated. Only the 3 upper sub-groups of psychology students had thresholds lower than the threshold of the least capable sub-group of orchestra members.

Incidentally, these data on thresholds have been used in deter-

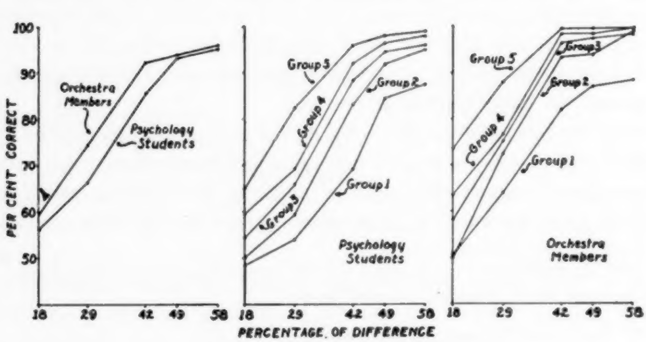

Fig. 5

Curves indicating how the mean percentage of correct responses increased with increase in the amount of structural difference between paired stimulus tones. Left-hand graph, for psychology students and orchestra members as a whole; middle graph, for 5 sub-groups of psychology students; right-hand graph, for 5 sub-groups of orchestra members.

mining how the test is to be revised. For example, the average threshold for the 317 psychology students was found to be approximately 35. Thus, the test might well have a series composed of 2 tones which differ in structure by about 35%. Such a series should turn out to be about midway in difficulty between Series 3 and 4.

TABLE VI

THRESHOLDS FOR TIMBRE DISCRIMINATION, WITH DATA USED IN THE LINEAR INTERPOLATION FORMULA TO COMPUTE THEM

Observers	N	X_1	X_2	P_1	P_2	T*
Psychology students	317	29	42	66.3	85.4	34.9
Group 1	60	42	49	69.0	84.5	44.7
Group 2	60	29	42	59.5	83.0	37.6
Group 3	60	29	42	65.8	88.3	34.3
Group 4	60	29	42	69.0	92.0	32.4
Group 5	60	18	29	65.0	82.3	24.4
Orchestra members	62	29	42	74.5	92.5	29.4
Group 1	12	29	42	64.0	82.0	36.9
Group 2	12	29	42	72.5	93.5	30.5
Group 3	12	29	—	75.0	—	29.0
Group 4	12	18	29	63.5	76.5	27.7
Group 5	12	18	29	73.5	88.0	19.1

* It should be remembered that these threshold values, expressed as they are in terms of percentage of structural difference, are probably too general to be of permanent significance. The writer is now engaged in an extended psychophysical investigation of timbre, and he has already found that thresholds vary as a function of such factors as frequency level, intensity level, and the number and distribution of partials. The values here reported should, therefore, be examined only in relation to the particular stimulus tones on which they are based.

Summary. A timbre test was constructed which was composed of 5 series of 20 stimulus pairs each, or of 100 stimulus pairs. The 2 tones of half of the pairs were the same in harmonic structure, while those in the remaining half were different in this respect. All of the tones were essentially alike in pitch, loudness, and duration. Observers were asked to judge whether the 2 tones in each stimulus pair were the same or different in timbre.

The test was recorded on phonograph records and was then

administered to 317 university students who were enrolled in classes in elementary psychology, and to 62 members of the university orchestra. The harmonic structure of the various tones used was determined by analyzing oscillograms of the tones, the oscillograms being made from the records.

The scores obtained by the 2 groups of observers were given statistical treatment. Among other things, internal checks were made on the test, reliability coefficients were computed, scores obtained by the orchestra members were correlated with scores obtained by them on the Seashore tests of pitch and intensity, and, finally, timbre thresholds of a general type were determined. The following conclusions seemed warranted:

1. Scores obtained on the test, particularly by the psychology students, tended to fall into a normal distribution. Consequently, there is reason to believe that the capacity measured by the test (ability to perceive timbre differences, presumably) is normally distributed.

2. Inasmuch as the mean score secured by the orchestra members was significantly higher than that secured by the psychology students, the test serves to differentiate between the capacity of musicians and the capacity of an unselected group.

3. Reliability coefficients for the test (psychology students, .68; orchestra members, .71) are not as high as could be desired, but they compare favorably with those obtained for the Seashore measures.

4. The test, in its present form, is fairly satisfactory, but it can undoubtedly be improved. The 2 easiest series differ little in difficulty, and one of them could be eliminated to make room for a new series. The internal checks made on the test revealed the approximate degree of difficulty which the new series should have.

5. The "sense of timbre" is probably not significantly related either to the "sense of pitch" or to the "sense of loudness."

6. Rigid psychophysical techniques must be employed to determine highly accurate and entirely meaningful thresholds for timbre discrimination, but general trends were indicated by the test results. Not only were orchestra members shown to be generally superior to psychology students; rather large differences in thresh-

olds were found for various sub-groups of both orchestra members and psychology students.

In conclusion, a word might be said about the feasibility of standardizing a timbre test for general use. It is now possible to produce and to make phonograph recordings of complex tones of predetermined structure. The tones can be "got on" the records. The question is whether they can be "got off" without excessive distortion. There are two major complicating factors. For one thing, any phonograph, be it electric or acoustic in type, has its own frequency-response characteristics; and the complex sounds that it will produce depend for their structure not only upon the record but also upon these characteristics. The second complicating factor has to do with room acoustics. The stimulation received by an observer in a reverberant room depends to some extent upon his position in the room. Further, the stimulation will vary from one room to another even though the sounds emitted at the source remain unaltered. It goes without saying that if the actual stimuli constituting a timbre test cannot be kept reasonably constant from group to group and from individual to individual, a satisfactory standardization of the test is not possible.

In the construction of the present test, an attempt was made to minimize the possible operation of complicating factors. This was done by choosing frequencies which the average phonograph will reproduce with a reasonable degree of fidelity and which have wave-lengths sufficiently long to avoid alternate live and dead spots within a small area in a room. Whether or not this precautionary step is enough to overcome the underlying difficulties in controlling the tones is a problem which must be specifically investigated. It seems reasonable to believe, however, that the actual stimuli will be stable enough to permit a suitable standardization of the test.

APPENDIX

An Optical Generator: Apparatus for Producing Complex Sounds

The generator was built to meet the need for apparatus with which synthetic complex sounds could be produced under controlled conditions, particularly for use in psychophysical investiga-

tions of timbre. The essential principle which underlies the apparatus is the same as that which underlies the variable-area method of reproducing sound from motion picture film. This principle involves successive and rapid variations in the amount of light which falls on a photo-electric cell.

A schematic drawing of the generator is shown in Fig. 6. The essential parts are a specially prepared disc, a rotating drum, a constant-speed motor with a gear box, an optical system, a photo-electric cell, a movable carriage, an audio-frequency amplifier, and a loud speaker (or earphones).

The disc, which is securely fastened on the drum, is revolved by the motor at a fixed speed, above the optical system. The photo-electric cell is mounted above the disc and directly over the optical

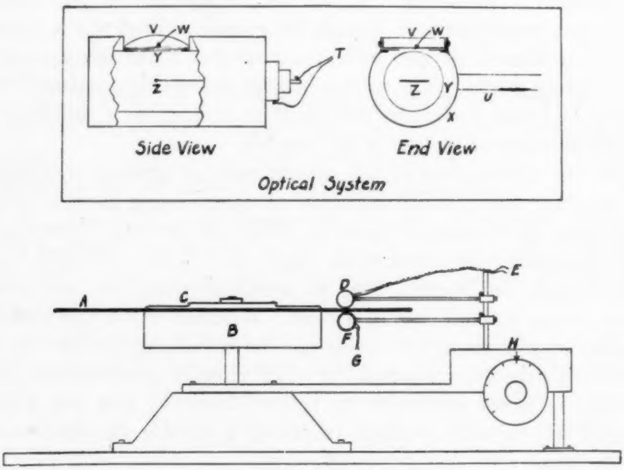

Fig. 6

Schematic drawing of the generator, and (at top) two drawings of the optical system.

A, disc; B, revolving drum; C, driving belt groove; D, photo-electric cell; E, input leads to amplifier; F, optical system; G, leads to 9 volts direct current; H, movable carriage.

T, leads to 9 volts direct current; U, supporting rod; V, cylindrical lens; W, slit; X, brass tube; Y, glass of lamp; Z, filament.

system. The amount of light which falls on the cell varies from instant to instant, the variations depending upon the adjustment of the movable carriage and the corresponding row of wave-like patterns on the disc. As a result, the output of the cell varies. The cell is connected to the input, and the loud speaker (or earphones) to the output, of the amplifier. The frequency of the resulting sound is determined by the number of wave-patterns in a single row on the disc and the rate of revolution of the disc. Its intensity is dependent upon both the r.m.s. value of the wave-pattern and the amount of amplification. The structure of the sound is con-

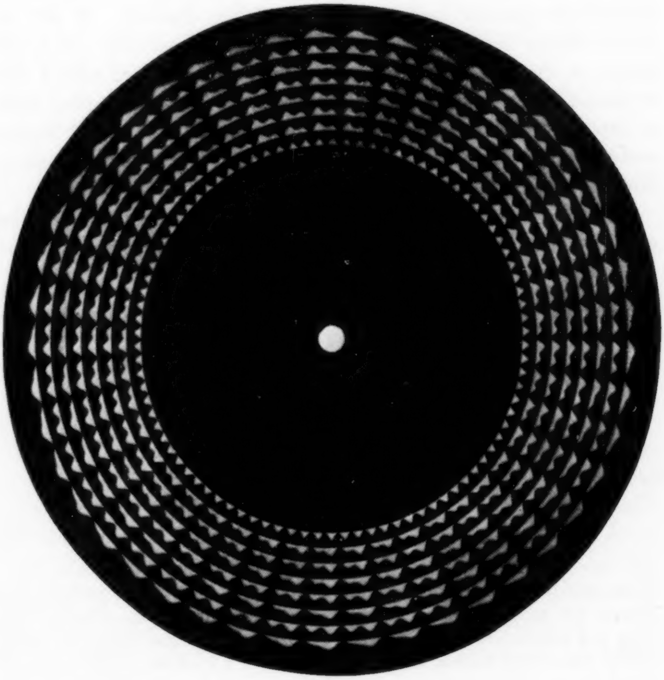

Fig. 7

Photograph of a disc used on the generator.

ditioned by the relationships which exist among the harmonic components of the complex pattern. The sound is turned on and off by means of a mercury-cup "cut-off."

Although each of the parts of the generator plays an important role, only the disc and the optical system will be described in considerable detail.

The disc. Fig. 7 is a photograph of one of the discs that have been prepared. (It is not the one used in constructing the timbre test.) A casual inspection of the figure will reveal a disc's most important feature—complex repetitive patterns.

The preparation of a disc is a rather long and tedious task, but the essential steps can be summarized quite briefly. The disc itself is a circular piece of heavy plate glass, 24″ in diameter. In its center, a circular hole exactly 1″ in diameter is bored. All radial distances on the disc, from this center hole, are measured with a pair of specially-constructed dividers. Distances around the disc (that is, along a given concentric circle) are measured in terms of degrees and minutes, the measurements being made with a highly-accurate dividing engine.

The curves to be cut on a disc are first expressed in mathematical form.[10] In this way, the r.m.s. value of any curve as well

[10] For example, the curves on the disc shown in Fig. 7, numbered from the periphery to the center, were determined by the following equations:

1. $y = \sqrt{7} \sin x + 1 \sin 2x$
2. $y = 1 \sin x + \sqrt{7} \sin 2x$
3. $y = \sqrt{6} \sin x + \sqrt{2} \sin 2x$
4. $y = \sqrt{2} \sin x + \sqrt{6} \sin 2x$
5. $y = \sqrt{5} \sin x + \sqrt{3} \sin 2x$
6. $y = \sqrt{3} \sin x + \sqrt{5} \sin 2x$
7. $y = 2 \sin x + 2 \sin 2x$
8. $y = \sqrt{8} \sin 2x$

Phase angles are not expressed, being zero in all cases. The various coefficients are proportional to anticipated pressure amplitudes. Control over total and relative intensity is made possible by the proper choice of coefficients. As is well known, the total intensity of a complex sound is proportional to the sum of the squares of the pressure amplitudes of its components; and the intensity of any one of its components is proportional to the square of that component's pressure amplitude.

as its harmonic structure can be definitely predetermined. Not only the number, the relative intensity, and the distribution of the components, but also their phase relationships, can be given mathematical expression.

Frequency is not represented mathematically but it is easily predetermined. The motor is geared down and, with different adjustments, will revolve the disc 4, 4.5, 5, 5.5, 6, 6.5, or 7 times a second. Hence, the number of curves in a given row on a disc multiplied by a given speed of rotation indicates the fundamental frequency which will be obtained. It is obvious that 7 different frequencies may be produced with any row of curves on a disc.

The actual process of plotting curves from equations and cutting them on a disc is too complicated to permit of full description here. However, two or three points of general significance should be stressed.

The curves are not painted on the glass but are traced with a sharp tool into a thin layer of high-grade quick-drying lacquer which is spread on the glass and allowed to attain a proper state of dryness. Then, certain portions of the lacquer are removed. In the work of tracing, thin brass patterns are used. These patterns are filed to exact proportions with the aid of curves which are plotted on heavy paper. When periodic sounds are desired, only one pattern is required for the cutting of a single row of curves. When modulated sounds are desired, many patterns must be prepared for a single row.

Another point of significance is that the curves are plotted and cut on curved instead of straight axes, and the y (or amplitude) values are plotted on radial lines. The radial segment which is to contain a given curve is accurately delineated with the dividing engine, and the radial lines within the segment can be spaced equally with the same instrument.

Finally, when a disc is completed, its accuracy can be checked in various ways. Information is thus secured on the actual physical properties of the sounds which can be produced with it.

The optical system.[11] The beam of light which falls on a row

[11] There are two schematic drawings of the optical system in the upper part of Fig. 6.

of curves must be long enough to extend from the highest (positive) to the lowest (negative) radial points of the curves and, theoretically, it should be infinitely narrow in width. The beam which is used meets the requirements in length, but it is .01″ wide.[12] This beam is secured in the following way:

An 8.5 volt, 4 amp. lamp (a so-called movie exciter lamp) is encased in a brass tube 1″ in diameter. The tube, which is closed at both ends, has a round hole in its side. This hole is .75″ in diameter and is directly over the straight filament of the lamp. The filament is approximately .3″ long. Although it consists of coiled wire, the coils are so close together that the emitted light is practically constant throughout the length of the filament. A circular piece of thin brass fits tightly in the hole in the tube and is fastened as close to the filament as possible. This piece of brass has in it a slit .3″ long and .005″ wide. The slit is parallel to the filament and directly over it. A small cylindrical lens of short focal length, which is placed on top of the slit, focuses a slightly widened image of the slit on the disc. The beam may be shortened by means of an adjustable shutter which is placed on top of the lens.

An iron rod which is connected to the movable carriage supports the optical system. The system is held about .1″ below the disc. It is so placed that the beam of light will be exactly parallel to any given radial line of the disc. This parallel relationship between the light beam and radial lines is very important,[13] and it is maintained regardless of which row of curves the optical system is directly below. Direct current of 9 volts is used in the system.

Other parts of the apparatus. The motor is necessarily of the constant-speed type. The gear box attached to it makes possible 7 different speeds of rotation of the drum and disc.

The drum is made of cast iron and is exactly counterbalanced.

[12] A width of .01″ is narrow enough. In reproductions of sound from motion picture film, the beam of light used is .001″ wide, but the film travels at a speed of only 90′ per minute. A point on the inside row of curves on a disc travels over 1,200′ per minute when the disc revolves 5 times per sec.

[13] It will be recalled that y (or amplitude) values are plotted on radial lines.

Its central shaft fits tightly in the hole in the center of the disc.

A Western Electric 1-A photo-electric cell has proved satisfactory. It is held about .25″ above the disc by a rod which extends from the movable carriage.

The movable carriage is fastened to the base of the drum. It is constructed in such a way as to permit of rapid, exact, and simultaneous shifting of the optical system and the cell—a feature which is essential for psychophysical work.

The amplifier is operated on direct current from batteries to prevent alternating current distortions. It has essentially uniform frequency-response characteristics over the range from 30 to 8,000 cycles.

When the generator is used in demonstrating varieties of complex sounds or in making rough measurements, with groups, of ability to discriminate structural differences, an RCA-Victor high-fidelity dynamic speaker is adequate. More rigid psychophysical measurements of discriminative capacity require the use of a calibrated Western Electric 555W receiver.

Accuracy of the apparatus. Measured electrical output of the generator corresponds closely to theoretical expectations. This correspondence is clearly revealed by the results of measurements made on sounds produced with the disc shown in Fig. 7.

Inasmuch as the r.m.s. value of each curve on this disc is equal to that of every other, the eight different sounds should have the same intensity. By actual check with a vacuum tube voltmeter, no sound was found to differ from another by more than .2 db.

A further check on the agreement between expected and actual output was made by means of harmonic analysis. The largest gross difference in structure was slightly less than 5%. All other differences were less than 3%.[14] Of course, the structure of the generator output does not agree exactly with the structure of the sounds as they are emitted by a loud speaker. For experimental purposes, the nature of the acoustic energy proper must be determined.

[14] These errors, expressed in intensity level units, were all less than 1 db. That is, a given partial had a relative intensity within 1 db of what was expected. When sounds of greater complexity are produced, the errors are somewhat larger but are typically less than 3 db.

Although the generator is not as flexible as one might wish, it meets many of the needs for which it was designed. Aside from its value as a research instrument, it serves as a convenient means of demonstrating varieties of timbre, subjective tones, and changes in loudness with changes in harmonic structure.[15]

[15] An electrostatic type generator has also been constructed for use in the Iowa laboratory. It was added to supplement the optical instrument. It provides for a high degree of flexibility, particularly in the manipulation of individual partials. A complete description of it is to be published at an early date.